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Gisela A. M. Dreschhoff
Edward J. Zeller

ANNUAL TECHNICAL REPORT

November 1, 1993

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Contracting Officer: Capt. Helen R. Tyson
Program Manager: Dr. Henry R. Radoski

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
BOLLING AFB, D.C. 20332-6448

REPORT DOCUMENTATION PAGE

Form Approved OMB No 0704-0188

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Public reporting burden for this collection of information is estimated to average ... gathering and maintaining the data needed and completing and reviewing the ... collection of information including suggestions for reducing this burden to Washington ... Davis Highway Suite 1204 Arlington VA 22202-4302 and to the Office of Management ...

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE 25 Oct 93	3. REPORT TYPE AND DATES COVERED ANNUAL - 1 Nov 92 - 31 Oct 93
4. TITLE AND SUBTITLE A NITRATE SIGNAL OF SOLAR FLARES IN POLAR SNOW AND ICE		5. FUNDING NUMBERS AFOSR-88-0065 61102F 2311 AS
6. AUTHOR(S) Dr Gisela A.M. Dreschhoff		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Radiation Physics Lab The University of Kansas Space Technology Center Raymond Nichols Hall,		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) AFOSR/NL 110 Duncan Avenue, Suite B115 Bolling AFB DC 20332-0001 Dr Henry Radoski		10. SPONSORING/MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES		
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimitd		12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Operations have been concentrated on the micro-resolution analysis of the 120 meter ice core that was collected in Greenland in June, 1992. Thus far, 64 meters of the ice core have been sampled and a total of over 4000 individual samples have been analyzed for both nitrate and electrical conductivity. It has been possible to identify a number of specific anomalies in both the nitrate and the electrical conductivity records. Strong nitrate anomalies related to known solar flares have been identified, and it will become possible to delineate a signal of solar activity well beyond the known geophysical records. It has also been observed that periods of known low solar activity also correlate with lower than normal nitrate concentration and yearly nitrate flux. A new automatic ice core melting apparatus has been designed and built that will permit sampling the remaining ice cores at a higher resolution than was previously possible. This is a significant advantage because deeper ice cores are more compacted and the higher sampling frequency will maintain nearly the same time resolution as that obtained nearer the surface.

14. SUBJECT TERMS			15. NUMBER OF PAGES
			16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT (U)	18. SECURITY CLASSIFICATION OF THIS PAGE (U)	19. SECURITY CLASSIFICATION OF ABSTRACT (U)	20. LIMITATION OF ABSTRACT (UL)

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)

SOLAR PROTON EVENTS FROM A 180 YEAR DEPTH PROFILE OF NITRATE CONCENTRATIONS FROM THE CENTRAL GREENLAND ICE SHEET

Summary

Operations throughout this funding period have been concentrated on the micro-resolution analysis of the 120 meter ice core that was collected in Greenland in June, 1992. Thus far, 64 meters of the ice core have been sampled and a total of over 4000 individual samples have been analyzed for both nitrate and electrical conductivity. It has been possible to identify a number of specific anomalies in both the nitrate and the electrical conductivity records. The conductivity sequence contains a signal from known volcanic eruptions and provides an especially effective dating system for specific portions of the core. Similarly, strong nitrate anomalies related to known solar flares have also been identified, and it will become possible to delineate a signal of solar activity well beyond the known geophysical records. We have been able to identify a major nitrate anomaly in the 1859-1860 period which is related to a specific flare that was optically observed in England by Carrington in 1859. We have also observed that periods of known low solar activity also correlate with lower than normal nitrate concentration and yearly nitrate flux. This is especially apparent in the lower part of the ice core that was deposited at a time when the solar cycle was much reduced when compared to the conditions over the last 5 solar cycles.

We have designed and built a new automatic ice core melting apparatus that will permit us to sample the remaining ice cores at a higher resolution than was previously possible. This is a significant advantage because deeper ice cores are more compacted and the higher sampling frequency will permit us to maintain nearly the same time resolution as that obtained nearer the surface.

SOLAR PROTON EVENTS FROM A 180 YEAR DEPTH PROFILE OF NITRATE CONCENTRATIONS FROM THE CENTRAL GREENLAND ICE SHEET

Nature of the Data and Discussion

A) The core was drilled in June 1992 at the GISP2 (Summit) drill site on the Greenland Ice Sheet. The core has a diameter of 4 inches and the samples were cut from the interior of the core under ultra clean conditions. The upper 12 meters of the core were sampled directly at the drill site on the Greenland Ice Sheet. The additional 52 meters of core were sampled in a class 100 clean room at the National Ice Core Storage Facilitiy at the Denver Federal Center where the remaining cores are stored.

B) Each sample is injected into a UV absorption cell for nitrate concentration analysis and simultaneously the electrical conductivity of the liquid in the same stream flow is determined (see Appendices A and B). The nitrate concentrations contain a signal of solar flares, whereas the conductivity is a measure of various anions and cations. Many times, large amounts of sulfates are known to be indicators of volcanic eruptions, thereby providing an additional tool for dating the snow sequence.

The nitrate sequence has been plotted in green and superimposed upon it in red is the electrical conductivity. The abscissa indicates the total sample number from 0 at the surface to 4056 at 64 meters depth. The ordinate represents nitrate concentrations in absorbance units (relative concentrations), and electrical conductivity in 10 uS/cm.

On pages 4-8 the complete depth profiles are shown. In the case of the electrical conductivity, major known volcanic eruptions have been highlighted. These volcanic signals in the snow can be used effectively as time markers at different depths in the firn. In the case of nitrate concentrations, some of the anomalous peaks (several standard deviations above the mean) have been indicated by the year of their occurrence. In some cases the fallout from the stratosphere of the nitric acid into the snow appears to be delayed by about one year. The preliminary assignments of nitrate anomalies to specific solar events will be reexamined after final dating of the depth profile with hydrogen/deuterium ratios.

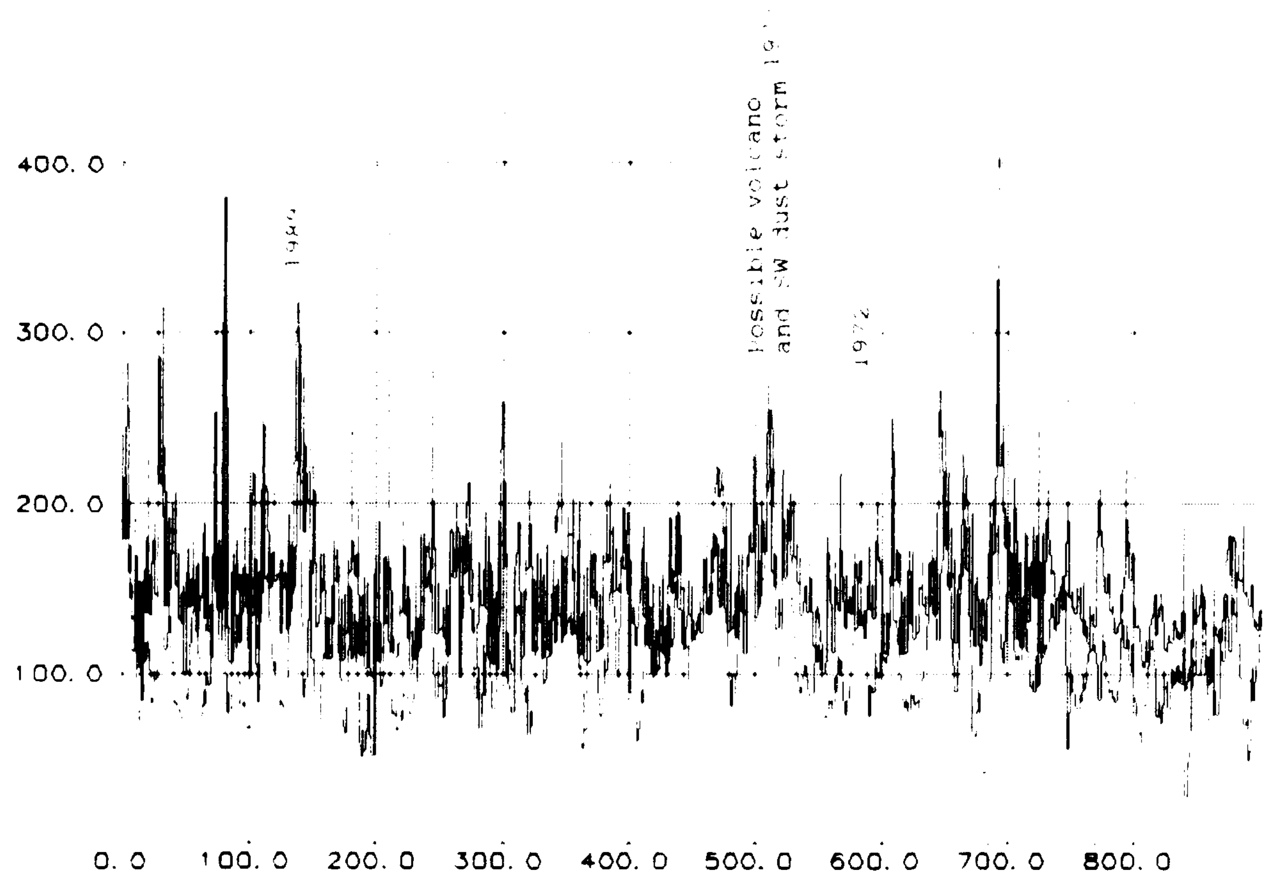
Preprint for 23rd Cosmic Ray Conference, Calgary, 1993

C) Some of the nitrate anomalies appear to be associated with irregularities within the frequency distribution of sunspot numbers similar to that which marks the 1972 flare in cycle 20. A noteworthy example is found in 1851 in cycle 9.

Using the present year assignments, we have constructed a curve of the mean annual nitrate flux, which is shown on page 10. A linear regression has been superimposed showing the trend toward increasing nitrate flux. This seems to mirror essentially the trend of the geomagnetic index.

D) We have completed a new apparatus to permit continuous melting through a 1 inch diameter cylinder in the interior of the core. Use of this apparatus will greatly increase our sampling resolution from 1.5 cm per sample to about 5 mm per sample. This apparatus is fully automated and will greatly facilitate our handling of the lower portion of the core which has a substantially increased density and is more difficult to sample by hand operation. The new apparatus will be used for subsequent core segments beginning in October, 1993.

Nitrate over Conductivity, GISP H Core



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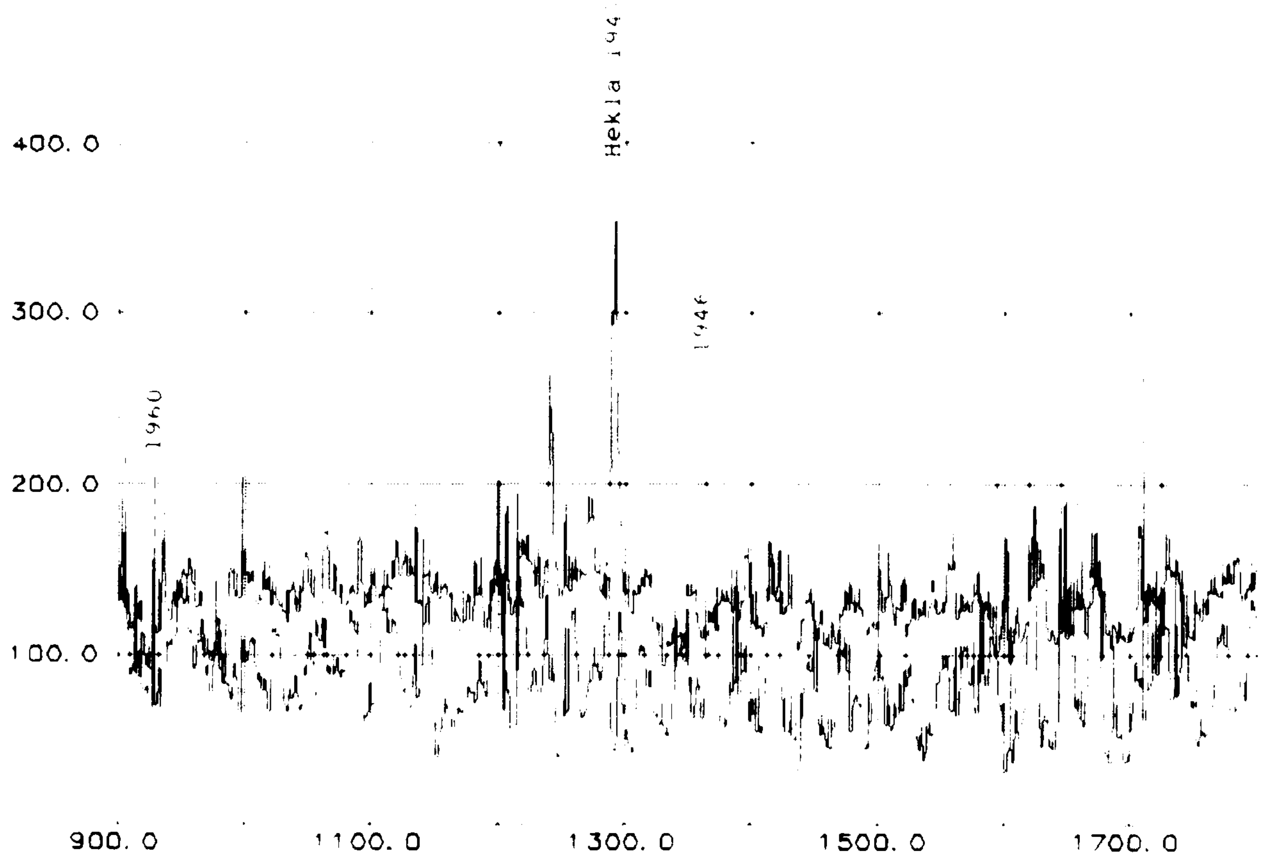

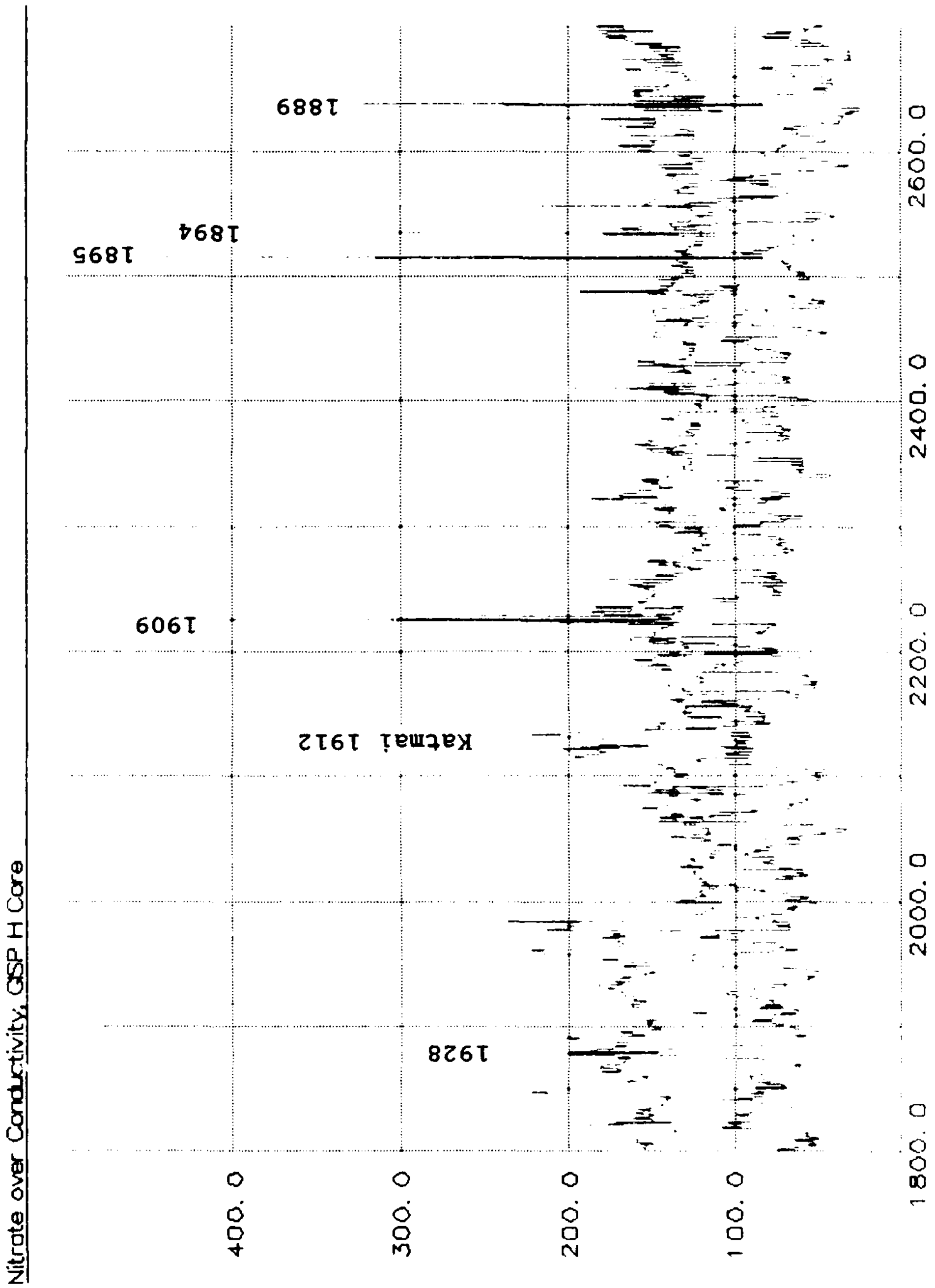
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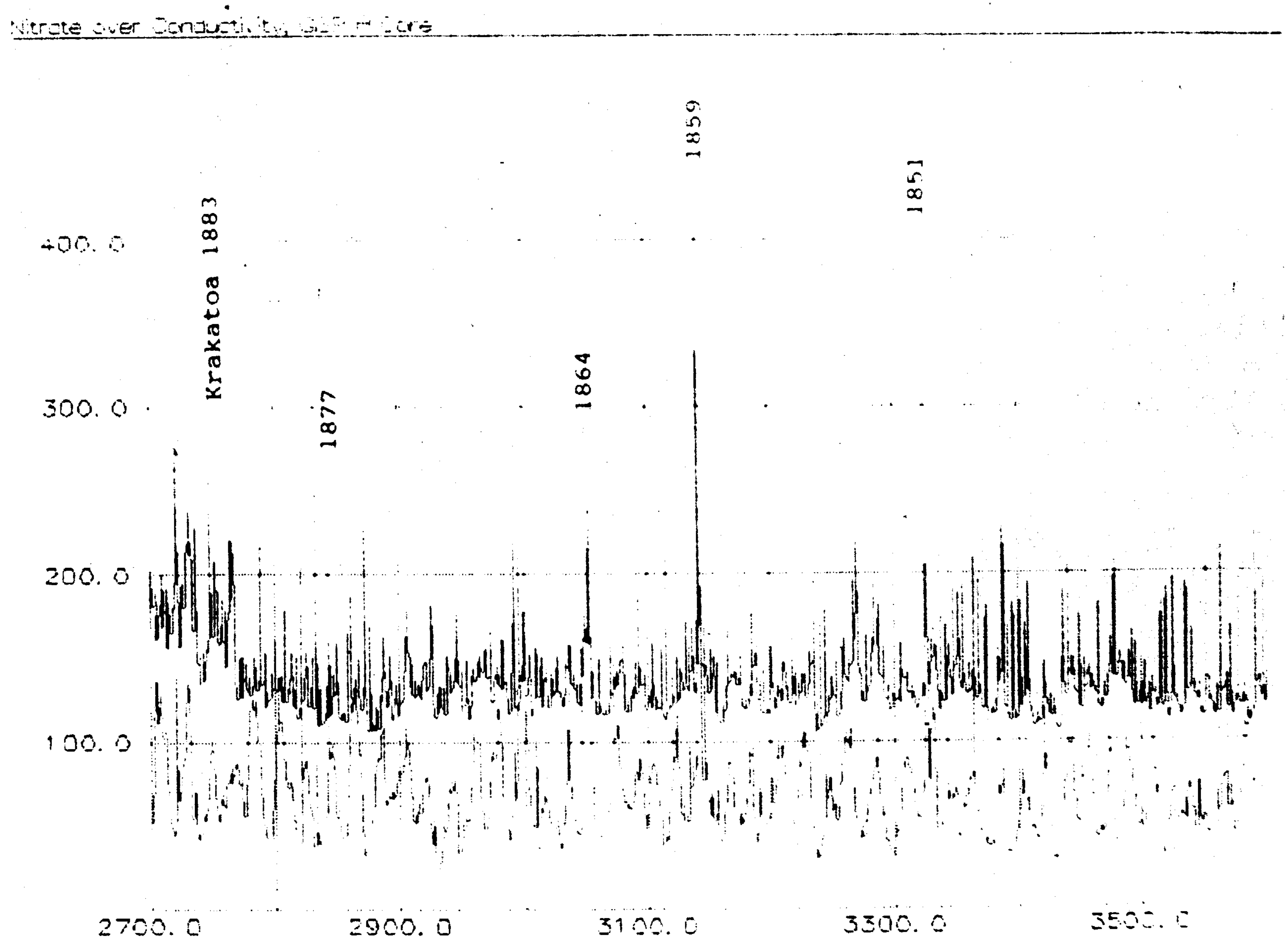
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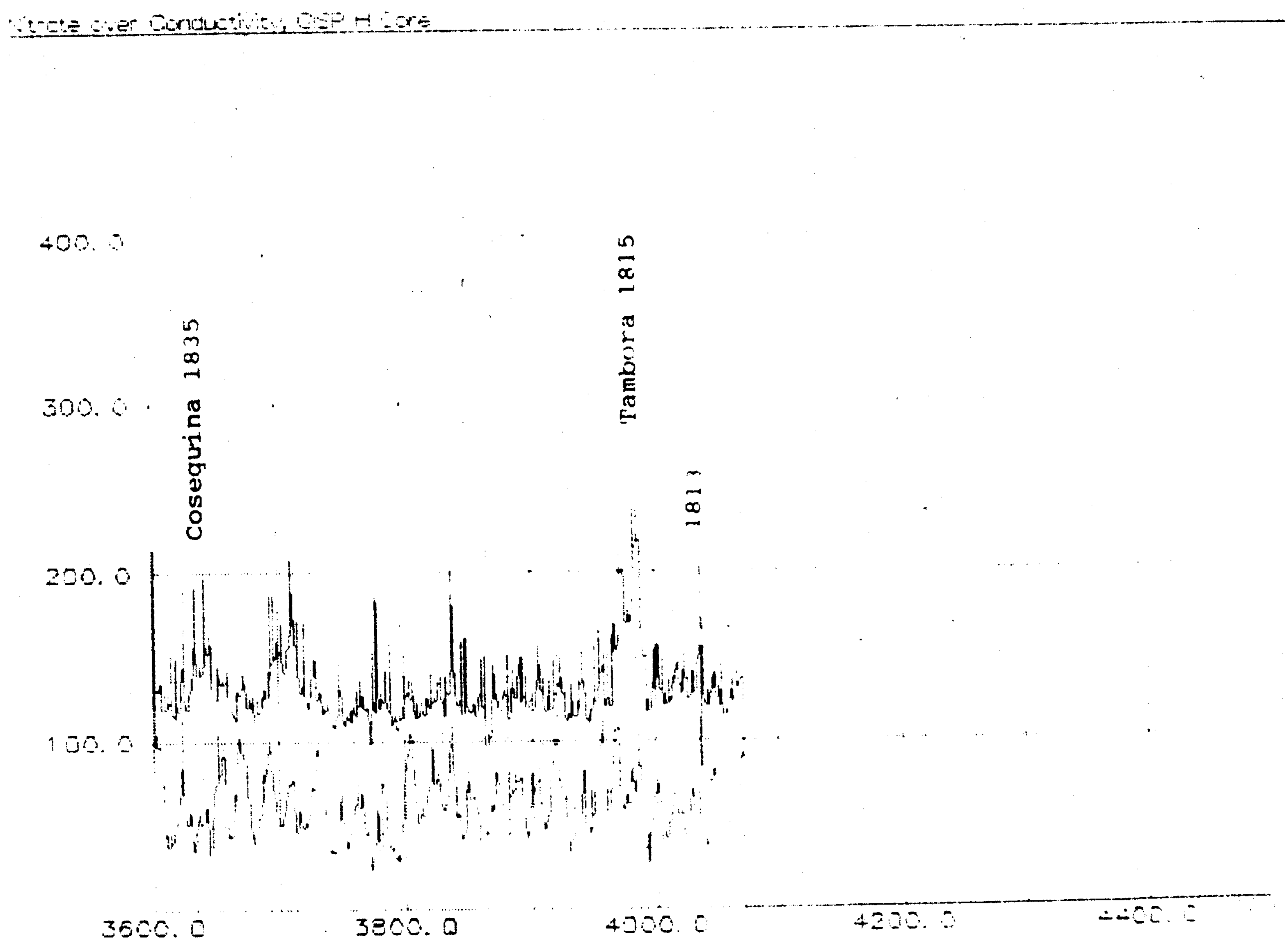
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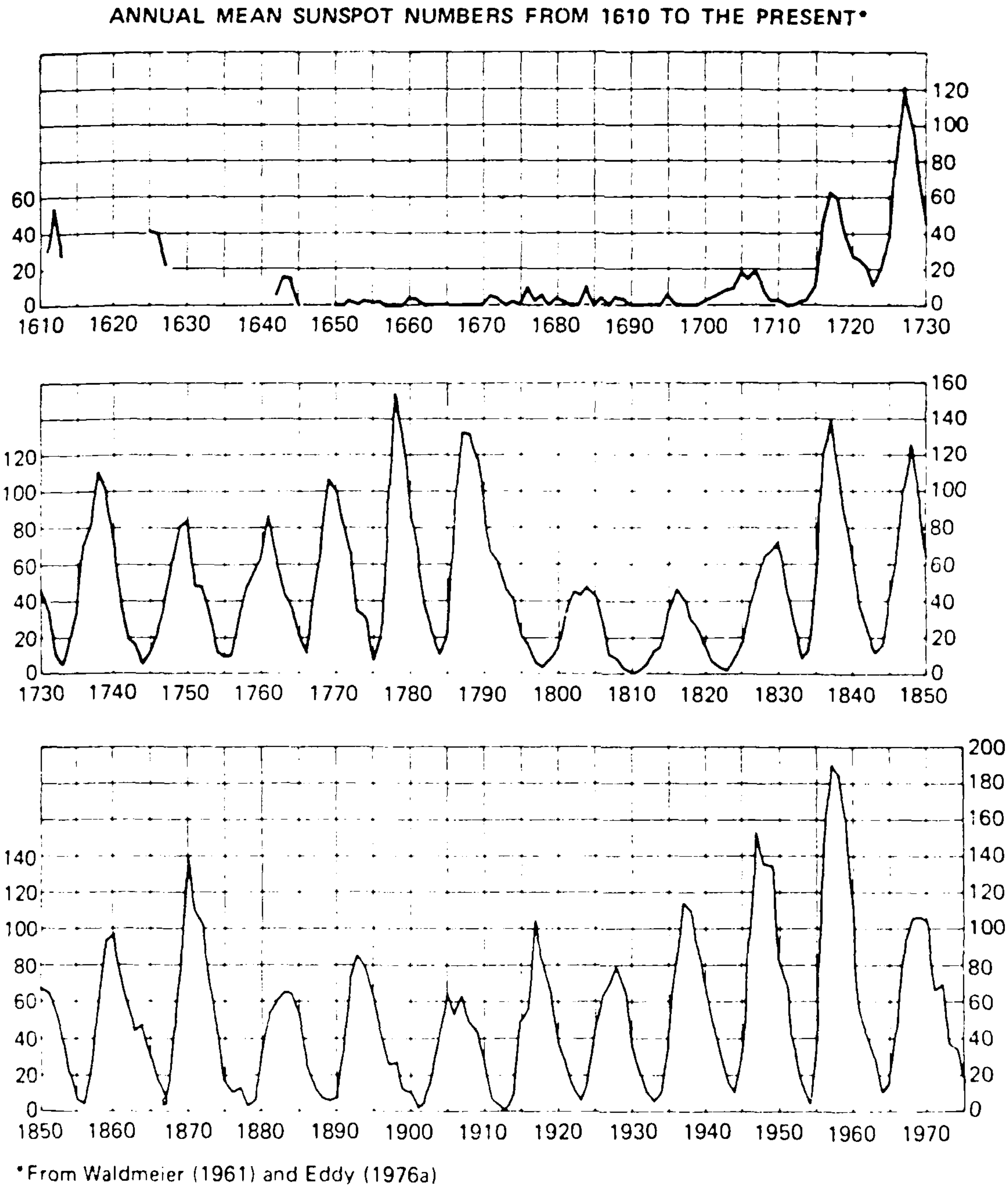
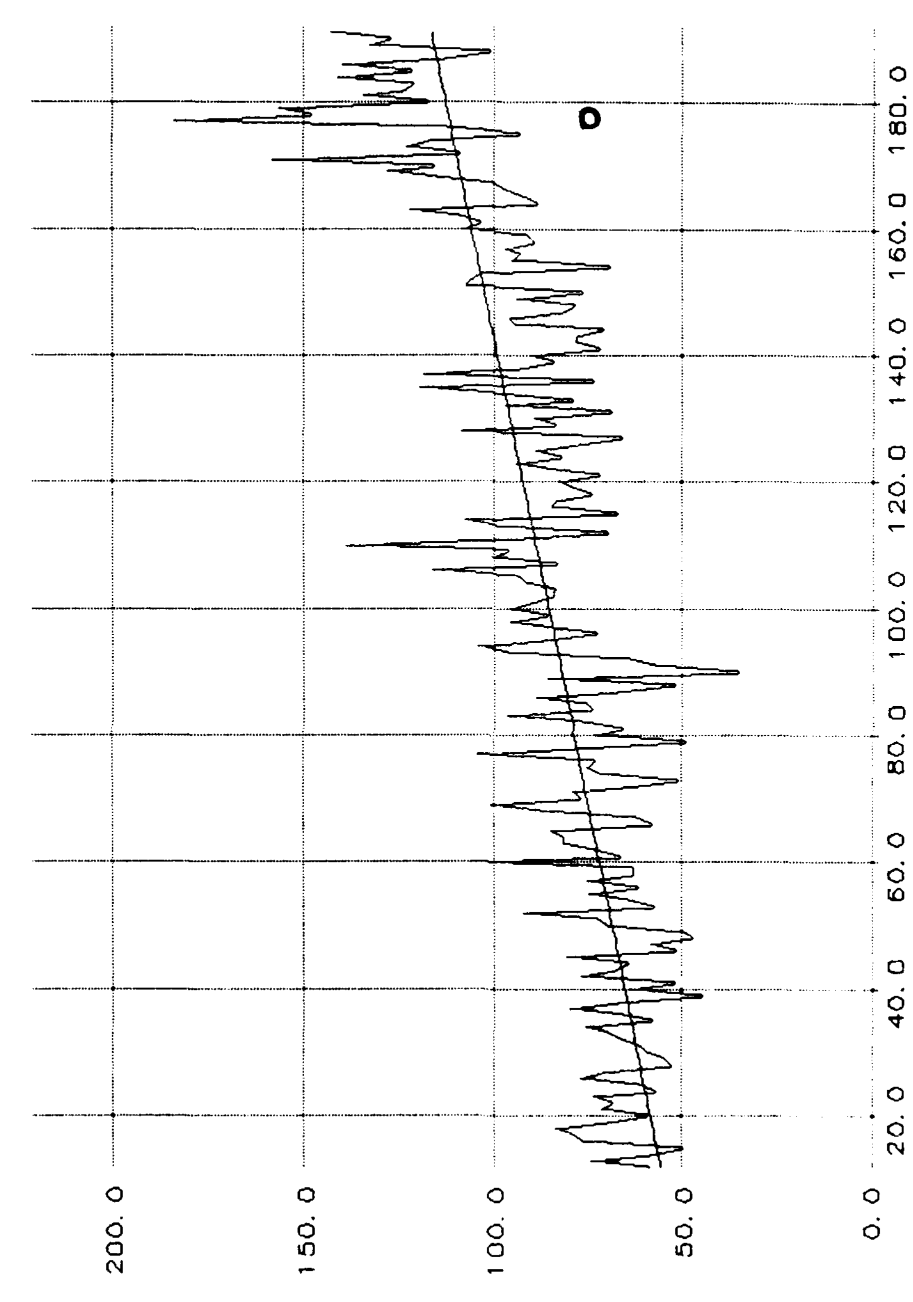


Fig. 2 Annual Mean Sunspot Number, A.D. 1700-1975, from Waldmeier (1961) and Eddy (1976).

Linear Regression Fit of Yearly Nitrate Flux



Interactions and Activities

1. During May, June and August of this year a substantial period of time was spent at the National Ice Core Storage Laboratory at the Denver Federal Center where we contacted the Technical Director, Dr. Joan Fitzpatrick, Dr. John Kelly, Director of PICO, and Dr. Robert Finkel, of Lawrence Livermore Labs.

2. G. Dreschhoff was asked to participate in the Polar Glaciology Antarctic Panel for two days in Washington, D.C.

3) G. Dreschhoff presented a paper at the 23rd Cosmic Ray Conference in Calgary (see Appendix B).

4) We coauthored a paper with M. A. Shea and D. F. Smart at the 23rd Cosmic Ray Conference (see Appendix C).

5) We coauthored a paper with G. Kocharov at the 23rd Cosmic Ray Conference (see Appendix D).

6) Several abstracts have been submitted for presentation at the Fall 1993 AGU Meeting (see Appendices E - H).

Adv. Space Res. Vol. 13, No. 9, pp. (9)443–(9)446, 1993
0273–1177/93 $24.00

MAJOR SOLAR FLARES AND LONG-TERM VARIABILITY IN ANTARCTIC ICE CORES

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ABSTRACT

In-Situ data acquisition of high-resolution nitrate concentration in Antarctic snow resulting from ionization in the polar atmosphere reveals (a) very large solar proton events can be resolved, (b) a signal from thermospheric and mesospheric sources is found across Antarctica within the average boundaries of the auroral oval, (c) long-term periods of high or low solar activity, such as the Maunder Minimum are present in the nitrate record.

INTRODUCTION

Our investigations on the Ross Ice Shelf, Antarctica, have shown that accurate and highly detailed information about past solar flare activity can be obtained from Antarctic ice cores by measuring the nitrate concentrations in continuous snow sequences with a simple and very rapid analytical technique, namely UV spectrophotometry. All measurements and data acquisition is performed in the field using ultra-clean, high resolution sampling techniques that have been described in detail /1/.

Solar cosmic rays that are incident upon the earth cause ionization in the polar atmosphere and generate NOx, including nitrate ions (NO_3^-). Making use of IMP 8 satellite data, ionization of the polar atmosphere has been reported to take place within the stratosphere and even at levels of $\geq$ 20 km for the high energy component of solar protons /2/.

Relatively rapid fallout of such ionization products to the surface of the Antarctic ice sheet is of critical importance if the resultant nitrate signal contained in the snow is to be resolved. Within the chemical and dynamical containment vessel of the Antarctic winter vortex, large scale downward motion exists and possibly downward flow taking place particularly rapidly near the vortex boundary /3/. A large role in the removal of nitrate from the atmosphere is played by the presence and build-up of polar stratospheric clouds (PSCs). It has been suggested that PSC particles may grow to about 10 µm to permit very rapid downward transport to the tropopause within several days and may be found as nitrate deposited in Antarctic snow /4/. Denitrification of the stratosphere with or without dehydration and nitrate fallout to the Antarctic surface is therefore best described as gravitational fallout or sedimentation /5/; /6/.

Auroral production of NO is shown to be the dominant source at high latitudes. Furthermore, nitric oxide increases within the mesosphere and thermosphere of up to a factor of 10 from periods of low to high solar activity as measured by the polar orbiting satellite Solar Mesospheric Explorer /7/; /8/. Results from the Nimbus 7 spacecraft on global nitric acid distribution show highest concentrations in the polar regions, particularly in the winter polar atmosphere /9/. With observations such as strong downward thermospheric winds measured at a coastal station when located under the equatorward edge of the auroral oval /10/, and possibly non-gaseous, particulate matter (hydrated NO_3^- ions) near the mesopause at very low mesospheric temperatures /11/, there is good evidence that signals from solar particle produced ionization products can even survive downward transport during the polar summer.

NITRATE SIGNALS OF SOLAR PROTON EVENTS FROM SOLAR CYCLES 22 TO 14

During the 1990-91 field season in Antarctica we drilled 29 meters of firn (compacted snow) core by hand and made simultaneous analyses on 1.5 cm snow samples for both nitrate and liquid conductivity using a Beckman Model 160 UV Spectrophotometer and an Orion Model 160 Conductivity Meter. The drill site is about ≤10 km away from the location of the 1988-89 Antarctic field season in which a 62 year high resolution analytical sequence from the Ross Ice Shelf showed strong anomalies that could be directly associated with specific major solar flare events /1/. In Figure 1, the equivalent primary peaks are labeled 1972, 1946, and 1928. Methods of dating the snow sequence, experimental techniques and descriptions of the area investigated are provided in earlier works /1/. In addition, to date our most recent snow sequence, we made use of the information from our previous, successive field seasons together with liquid conductivity data.

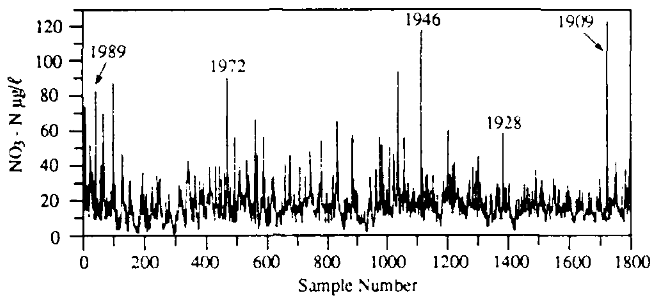

Fig. 1. Nitrate concentrations (µℓ$^{-1}$ as NO_3 - N) in a firn core from Windless Bight, Antarctica, to a total depth of 29 m. No adjustment for compaction has been made. Anomalous peaks are indicated by years of their occurrence.

It is important to recognize that the primary peaks that have been interpreted as the August 1972 SPE, July 1946 SPE, July 1928 white light flare, are very clearly present in both the 1988-89 ice core sequence and in the 1990-91 ice core as well. Their statistical significance is extremely high. The peak associated with the August 1972 event rises ~6 standard deviations above the mean. Similarly, the nitrate peak associated with the July 1946 SPE rises more than ~9 standard deviations above the mean, and for the year 1928, the maximum rises to ~4 standard deviations above the mean. This result is completely verified by repeat sampling of these primary peaks. Differences in the secondary peaks between both time series is very apparent and mostly due to depositional effects between the two drill sites.

Another highly significant peak in nitrates (16 standard deviations above the mean) near the maximum depth of our most recent firn core is clearly associated with a visible, pale dust layer approximately 3 cm thick, and has been dated as the year 1909. It is perhaps premature to associate this peak with a specific SPE but stratospheric air may have reached the ground bringing down the nitrates. Following the nitrate fallout two large conductivity peaks may represent sporadic (volcanic) stratospheric sulfate /12/, having its origin in nearby Mt. Erebus. This was confirmed by SEM and simultaneous chemical analysis of dust grains associated with the samples. The few dust grains associated with the NO_3 maximum do not show this composition characteristic of Mt. Erebus.

AURORAL ZONE FOOTPRINT IN ANTARCTIC SNOW

In a foot traverse of 5736 km from July 1989 to March 1990 /13/ surface samples were collected on a daily basis between geomagnetic latitudes 50° S West longitude and 77° S East longitude. They were shipped frozen and analyzed in the laboratory for nitrate concentrations. It has been concluded that anomalous nitrate concentrations are either due to nitrate production by ionization from e$^-$ precipitation and solar particle influx into the upper polar atmosphere (a) near the geographic South Pole or maximum auroral zone /14/ and

(b) near stations of the traverse, which may be associated with very penetrating e⁻ precipitation in the magnetic South Atlantic Anomaly /15/.

LONG-TERM SOLAR ACTIVITY IN SNOW SEQUENCES

Firn cores from South Pole (108 m) and Vostok Stations (101 m) on the high polar plateau of Antarctica have been analyzed for trace levels of nitrate /16/. Time series were constructed from the nitrate concentration data and have been subjected to harmonic analysis. Within the constraints of uncertainties in core dating both time series display periodicities that are assignable to solar activity cycles /17/, whereas the better dated upper 200 years of South Pole snow clearly shows the 11 year cyclicity of the sunspot cycle and 22 year periodicity of the Hale cycle.

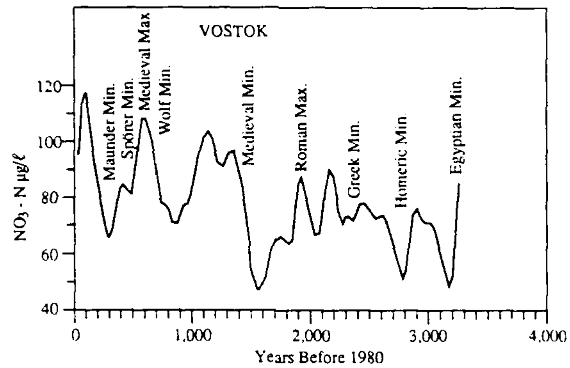

Fig. 2. Cubic spline fit to 20 year averages for nitrate concentration from 1346 data points from the complete Vostok firn core. Historical, solar and climatic data are superimposed.

The two time series are separated by more than 800 km on the Antarctic ice sheet. Both curves show similar trends that must be the result of a process affecting the middle atmosphere over the central part of the Antarctic polar plateau. By applying a cubic spline fit to both time series, broad periods of maxima and minima are displayed which show a close anticorrelation with the carbon-14 record for the equivalent time period. Both nitrate records show the period of known reduced solar activity, the Maunder Minimum from about 1645-1715 with very low nitrate values. Other periods of varying solar activity, particularly the Medieval Maximum is clearly displayed in a general rise in average nitrate concentration. Extending the cubic spline fit to the complete Vostok core, periods lasting several hundred years of lower and higher average nitrate concentrations are seen throughout the 3200 years of record. Approximate historic time periods known from climatic records and carbon-14 variation studies are indicated on the graph in Figure 2. Similar variations have been found recently in the upper part of the deep ice core currently being drilled on the Greenland ice sheet where nitrate concentrations parallel the timing of the Little Ice Age (Maunder Minimum Period) and the Medieval Warm Period in addition to a relatively strong 12-year periodicity during the Medieval Maximum /18/.

DISCUSSION AND CONCLUSIONS

The primary condition for detection of a specific solar proton event (SPE) seems to be a combination of the winter polar vortex and high particle numbers like that of the August 1972 flare which produced a fluence of 10^{10} protons (cm^{-2}) at the 10 MeV energy level during a period of several days /19/. On the other hand, the ground level event (GLE) of September 1989, the largest GLE in 33 years /20/ may have produced the spike of ~6 standard deviations above the mean during the snow deposited in 1989 (Sample number 38, Figure 1). The amplitude of this spike is only defined by a single point and would need to be verified later in a sequence analyzed at even higher resolution (2-5 mm). Improvement is especially needed in dating snow sequences.

This work was suported by U. S. Air Force contract AFOSR 88-0065 and National Science Foundation Grant DPP 8919190.

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Preprint for 23rd Cosmic Ray Conference, Calgary, 1993

The Solar Signal from Cycles 14 to 22 in Nitrate Concentrations in Antarctic Snow

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ABSTRACT

Nitrate concentrations measured at very high resolution in Antarctic snow (average sampling interval on the order of magnitude of about 2 weeks) contains a signal of solar activity caused by associated atmospheric ionization. The analytical sequence shows short-term pulses that can be related to known solar proton events. The unambiguous detection of the events seems to depend primarily on the presence of the Antarctic winter vortex which is related to the dynamics of the terrestrial polar atmosphere.

1. INTRODUCTION

Varying levels of nitrate (NO^-_3) concentration in Antarctic snow are, in part, the result of ionization in the upper and middle atmosphere caused by energetic solar protons in the auroral region and within the polar cap (Dreschhoff and Zeller, 1990; Dreschhoff and Zeller, in press, Qin, et al., 1992). Significant increases in ionization down to lower stratospheric levels is essential if this signal is to be recognizable as an individual event on the ground in the snow sequence of nitrate concentrations in Antarctica. This suggested process is substantiated by balloon measurements at 26 km altitude (Holzworth et al., 1987). Doubling of ion conductivity and vertical current densities in the polar stratosphere were observed for the short duration of the very energetic but relatively low fluence February 1984 solar proton event (SPE). Much longer vertical current density enhancements were reported for the August 1972 proton event sequence. Subsequently, transport to the ground may be accomplished via cloud physics processes and the formation of stratospheric HNO_3 (nitric acid). Indirect verification of this concept is indicated by highest levels of nitrate concentrations in snow samples that have their origin nearest to areas of transport from altitudes of the auroral zone to the ground (Mulvaney and Wolff, in press).

2. THE SOLAR SIGNAL FROM NITRATES FROM CYCLES 14 TO 22

We will examine enhancements in nitrate concentrations due to short term solar proton events and due to variations in the solar cycles. Figure 1a contains the complete record of 1800 data points of nitrate concentrations in 29.4 meters of vertical column profile. The major nitrate peaks and the year of their occurrence have been marked in Figure 1a. It is possible to calculate yearly nitrate flux data (Figure 1b). Each data point represents the nitrate flux for the individual years from 1905 at maximum depth of 29.4 meters, to 1990, the surface at the time the drilling was completed. A visual comparison is made with the yearly sum of the Ap* geomagnetic index for all Ap* values ≥ 85 (Figure 1c). This index is available for the years 1932 to the present. The general agreement between both data sets can easily be recognized without any attempt to smooth or manipulate the data in any form.

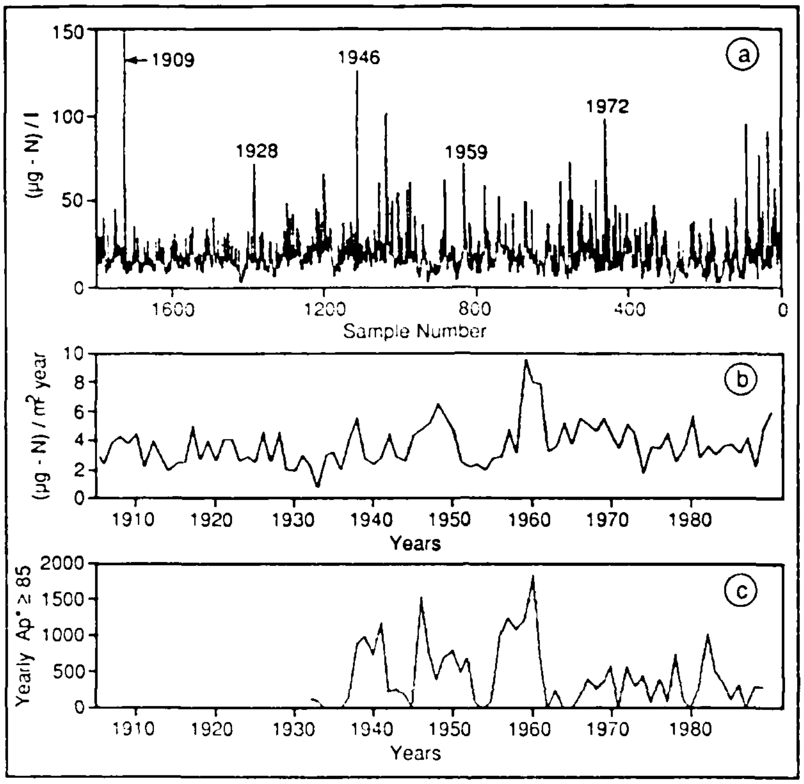

Fig. 1: (a) Variations of nitrate concentrations in µg-Nitrogen/liter from a total depth of 29.4m representing the year 1905 (sample number 1800) to the snow surface, representing the year 1990. Major peaks are identified by their year of occurence in the sequence. (b) Yearly flux values in (mg-Nitrogen)/m² year of sequence (a). (c) Yearly values of the geomagnetic Ap* index for Ap* ≥ 85.

It should be noted that the nitrate enhancement dated as the year 1909 is an extremely prominent peak but the presence of this high nitrate peak in Antarctic snow has been identified for the first time in this one snow sequence at a depth of almost 29 meters. Further study will be necessary to identify the origin of this peak. However, all other peaks have been verified in a number of field seasons by redrilling and resampling the snow sequence at Windless Bight on the Ross Ice Shelf in Antarctica. They have been dated as being coincident with SPEs (August 1972, July 1959, July 1946), or extremely large geomagnetic storms (July 1928 and September 1909). The time of these events coincides with a period when downward transport within the Antarctic winter/ early spring vortex is most efficient.

Solar parameters, as they may reflect conditions in the heliosphere and coupling to the magnetosphere by charged particles ultimately having relatively easy access to the earth's polar atmosphere, are summarized in Figure 2. Solar activity expressed in sunspot areas shows an asymmetry between the southern and northern hemispheres as

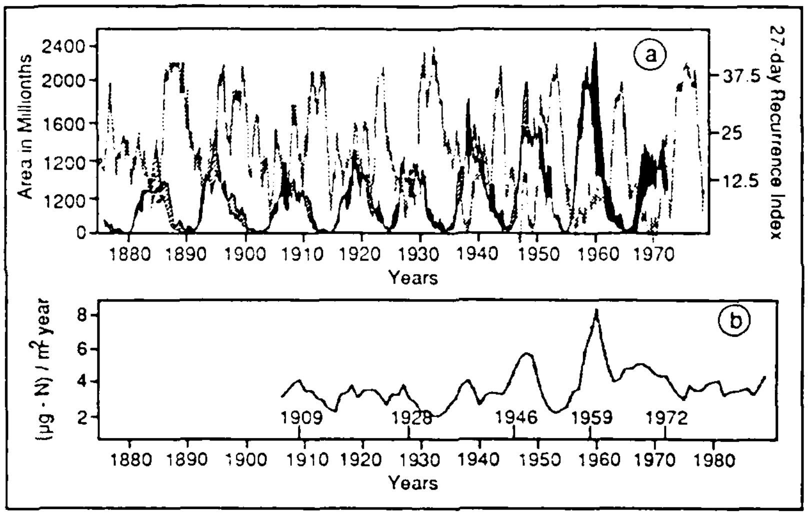

Fig. 2: (a) Distribution of excess sunspot areas in the morthern hemisphere (black) and southern hemisphere of the sun (cross hatched). The 27-day Bartels rotation-geomagnetic Recurrence Index (adapted from Sargent, 1979) has been superimposed (in grey) on the profile of the north-south asymmetry of sunspot areas. (b) 3-year moving average of the yearly nitrate flux profile in Fig. 1b, showing the 11-year cyclicity of solar activity. The locations of the major nitrate peaks have been indicated by bars on the bottom of the graph.

presented in Figure 2a. The dark sections between the two lines indicate periods with an excess of sunspots in the northern hemisphere of the sun, whereas the cross hatched sections indicate excess sunspots in the southern hemisphere (Shea et al., 1989). These large vatiations between the two solar hemispheres are essentially in phase with each other as well as with the total sunspot number (Swinson et al., 1986). If these data are compared to a 3-year moving average of the nitrate flux sequence (Figure 2b), it is clearly apparent that there is good agreement in the trends shown by the graphs of both of these data sets. However, the large nitrate peaks that we interpreted as being caused by major solar proton events and here indicated by bars in Figure 2b, can be divided into two groups. One group resulted from flares in the northern hemisphere (August, 1972, and July, 1946) and the other was associated with active regions in the southern hemisphere (July, 1928, and September, 1909).

Of primary importance in determining the degree to which the transit of charged particles will be facilitated from the sun to the earth is (a) the location of the flare relative to the solar central meridian (as seen from the earth) and (b) the condition of the interplanetary magnetic field. The heliolongitudinal positions for the flares that coincide with the largest and most conspicuous nitrate peaks seem to be associated with extended sequences of activity near the central meridian of the sun. Furthermore, we find, that there are common conditions for these nitrate peaks. For this we examine the so-called 27-day Bartels solar rotation-geomagnetic Recurrence Index (Sargent, 1979). This index is a good indicator of ordered conditions in the heliosphere during solar activity minima and "chaotic" conditions at the extremes of solar activity maxima, when a succession of

shock fronts move outward into the heliosphere. As can be seen in Figure 2a, except for 1959, all other large nitrate peaks are located just at or after a phase of short duration increase of the Recurrence Index within a period of normally low index numbers.

Figure 2b shows the Recurrence Index which has been superimposed on the graph for north-south asymmetries. It was noted by Sargent (1979) that the 27-day Recurrence Index shows the strongest response during the priod from about 1920 to 1977. This is an observation that follows closely the observation of Shea et al., (1989) that shows that the asymmetries of the solar hemispheres, once established, tend to persist for periods longer than a single solar cycle. In addition, there are indications that minima of the yearly flux values of nitrate in Antarctic snow (plotted as a 3-point moving average) vary in terms of their width or the time period of their width (between even and odd numbered cycles). These periods are coincident with the Recurrence Index exhibiting the same general behavior. If additional research continues to show these trends when more core sequences are examined, it may be possible to establish nitrate analysis of polar snow as a surrogate for previous activity cycles on the sun. This hypothesis gains support from the work reported in Simon and Legrand (1992), in which they find that not only are the sources of the dipole field deep seated in the solar interior but that they also exhibit a rigid 27-day rotation. Similarly the source for the bipolar fields emerging at "sunspot latitudes" are also subject to rigid to 27-day rotation and survive through several solar cycles. These results may provide a partial explanation for the response in the Recurrence Index and for the persistence of some of the observed north south asymmetries through relatively long periods of time.

3. CONCLUSIONS

The analysis of an 86 year nitrate (NO^-_3) sequence in Antarctic snow leads to the following conclusions: The concentration record contains a signal from individual SPEs, (2) The yearly flux curve indicates clear evidence of the ~11 year cyclicity of solar activity without statistical manipulation, (3) The conditions within (a) the heliosphere and (b) the antarctic polar atmosphere have a strong influence on the signal of solar output contained in snow.

ACKNOWLEDGEMENTS

This work (University of Kansas) was funded by the U.S. Air Force, grant AFOSR-88-0065.

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Preprint
23rd Int. Cosmic Ray Conf., July 1993

Appendix C

1

The Flux and Fluence of Major Solar Proton Events and their Record in Antarctic Snow

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ABSTRACT

A study of the major solar proton events since 1955 has shown that the large fluence events are likely to be associated with a solar flare source near the central meridian of the sun while the events with large peak proton flux are likely to be associated with solar flares near the west limb of the sun. We compare the solar proton events to the measurements of nitrate concentrations in the Antarctic ice and find that the largest concentrations are associated with the major fluence events. From these results we are able to assign a probable solar proton event source to three of the major peaks in the nitrate record prior to 1955.

1. DATA BASE

The longest homogeneous record of solar proton events is that derived from cosmic ray measurements. Between 1933 and 1953 cosmic ray measurements were obtained by ionization chambers responding primarily to the muon component which for solar cosmic rays represents a threshold of 4-5 GV. Four GLEs were reported between 1942 and 1951 using these detectors

Since 1953 routine cosmic ray measurements have been obtained from neutron monitors. High latitude neutron monitors record the cosmic ray intensity above ~ 1 GV which is a considerably lower threshold than the threshold of a muon detector. There have been 50 ground-level enhancements recorded by neutron monitors since the start of routine measurements in 1953.

In reviewing the GLE data acquired since 1942, Smart and Shea (1991) ranked the events according to the maximum amplitude increase recorded at the cosmic ray station having an asymptotic cone of acceptance viewing into the probable interplanetary magnetic field direction. This ranking, together with the location of the solar flare associated with the proton acceleration is given in Table 1.

Table 1. Largest GLEs (1955-1992) Using the Peak Flux Criterion

Rank	Date	Flare Location	
1	23 Feb 1956	23 N	80 W
2	19 Nov 1949	2 S	70 W
3	29 Sep 1989	24 S	~105 W
4	25 Jul 1946	22 N	15 E
5	28 Feb 1942	7 N	4 E
6	7 Mar 1942	7 N	90 W
7	4 May 1960	13 N	90 W
8	7 May 1978	23 N	72 W

Although routine spacecraft measurements of solar proton intensities did not commence until late 1965, several attempts have been made to estimate the solar proton fluence for the major events of the 19th cycle. A summary of the largest fluence events from Shea and Smart (1990) and Shea et al. (1992) is given in Table 2. All events with a fluence > 5 x 10^9 above 10 MeV are listed. The events listed in Table 2 do not include any entries prior to the 19th solar cycle since fluence data have not been derived for those events.

Table 2. Largest Solar Proton Fluence Events (E > 10 MeV) - 1955-1992

Rank	Date	Fluence	Solar Circumstances	
1	12-15 Nov 1960	3.4×10^{10}	Flares 4 W - 35 W	Major GMS
2	19-30 Oct 1989	1.9×10^{10}	Flares 9 E - 81 W	Major GMS
3	10-17 Jul 1959	1.5×10^{10}	Flares 60 E - 31 W	Major GMS
4	2- 7 Aug 1972	1.1×10^{10}	Flares 35 E - 37 W	Major GMS
5	22-26 Mar 1991	9.6×10^{9}	Flares 29 E - 26 W	Major GMS
6	12-18 Aug 1989	7.6×10^{9}	Flares 36 W - 88 W	Mod. GMS
7	10-12 May 1959	5.5×10^{9}	Flares 47 E - 26 E	Mod. GMS

2. SOLAR LOCATION OF ASSOCIATED REGION

From an inspection of Table 1 we note that four of the events occurred prior to the 19th solar cycle. The other four events having a large peak proton flux are not listed in Table 2. From Table 1 we also note that the majority of events with a large peak proton flux are associated with solar flares on the western hemisphere of the sun (or slightly behind the western limb). These events are typified by a rapid increase to maximum intensity followed by a smooth decay; the earth is usually not in a good position to be severely impacted by any associated interplanetary shock.

The events listed in Table 2 are primarily from what we call episodes of activity - a period when one active solar region crosses the solar disk during which several powerful solar flares generate a sequence of solar proton events, interplanetary shocks, and subsequent geomagnetic disturbances. Quite often the succession of interplanetary shock structures re-accelerates the already enhanced solar proton flux to higher energies than were originally present. The August 1972 series of events is an excellent example of a solar proton flux at the earth being enhanced with the arrival of the interplanetary shock wave (Levy et al., 1976; Smart et al., 1990). Ground-level events occurred for all the events in Table 2 except for the March 1991 and May 1959 sequences of activity; however, the peak relativistic solar proton flux for each of those events did not meet the peak flux amplitude necessary to be included in Table 1.

Major geomagnetic activity occurred in association with all of the solar flares and proton events listed in Table 2. We have used the Ap^* index to evaluate the magnitude of the geomagnetic disturbances (Allen, 1982). The ap index is a linearization of the pseudo-logarithmic Kp index and is derived for each three-hour interval. The Ap^* index is derived using a running mean to establish the most disturbed 24-hour period (instead of a standard UT day). This index is available from 1932 to the present time. Any 24-hour period with an Ap^* index > 40 is considered to be a magnetically disturbed period.

Using the Ap^* index, we find that the first six sequences of activity in Table 2 have Ap^* values > 150 indicating an extremely disturbed period. These events rank in the top 45 events on this list for the 20 year period. The 24-hour period commencing 2100 UT on 12 November 1960 has an Ap^* value of 293 and is No. 2 on the list. The remaining two events (No. 6 and 7 in Table 2) are associated with moderate geomagnetic disturbances with Ap^* values of 77 and 113 respectively.

From this we conclude that solar proton events with major fluences tend to be associated with solar activity near the central meridian of the sun; those events with large peak proton fluxes tend to be associated with solar activity near the western limb of the disk.

3. EVENTS PRIOR TO 1955

It is difficult to determine solar proton fluence for events prior to 1955. Two of the events in Table 1 are associated with solar activity near the central meridian of the sun; therefore it appears reasonable to assume that these flares were part of activity sequences. The 25 July 1946 flare was the progenitor of the geomagnetic storm on 26-27 July with an Ap* value of 212 (No. 19 on the Ap* list). The 28 February 1942 event appears to be associated with an Ap* value of 132 on 1-2 March. The GLEs on 28 February 1942 and 24 July 1946 have been the only GLEs attributed to solar flares near the central meridian of the sun that produced an increase on the ionization chambers or the muon telescopes. Consequently we conclude that these were, indeed, major solar proton events.

4. RESULTS FROM THE ANTARCTIC SNOWS

Figure 1 shows the peaks in nitrate concentrations in ice core samples taken in Antarctica (Dreschhoff et al., 1993). Throughout several core samples, there are persistent peaks at 1928, 1946, 1959 and 1972; the peak at 1909 is present in the only sample analyzed that includes snow back to 1905. The peaks in 1959 and 1972 coincide with large solar proton fluence events. The 1946 peak coincides with a major high energy solar cosmic ray event attributed to a white light flare at the central meridian of the sun and subsequently associated with a major geomagnetic storm.

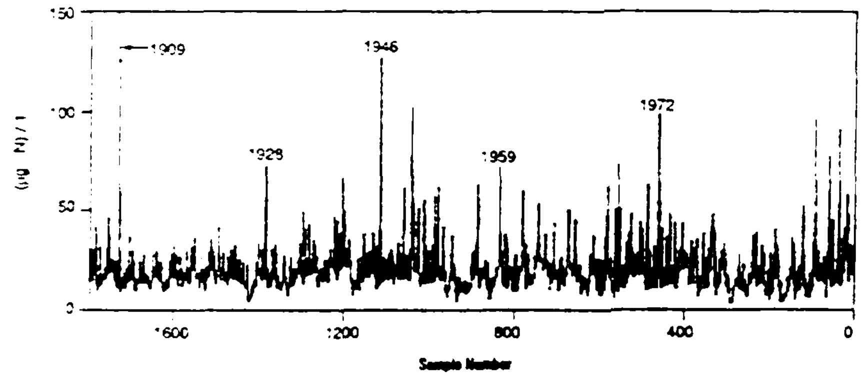

Figure 1. Nitrate concentrations in ice core samples taken in Antarctica.

Solar proton events that occur when the Antarctic polar vortex is present are more likely to be identified by the nitrate method than events that occur when the polar vortex circulation pattern is absent. The polar vortex is present primarily from June through August; however, the duration of the Antarctic polar vortex is highly variable year to year and has been known to start as early as May and extend into November. The major solar proton events in 1946, 1959 and 1972 occurred during the austral winter months when we expect the Antarctic polar vortex to exist. Since the event in 1946 was associated with a major geomagnetic storm, and since the ionization chambers recorded increases of the order of 15-20% from this central meridian flare (something that has not been equalled from any other central meridian flare in recent times), we conclude that the event in July 1946 was not only a major solar proton fluence event but probably contained more particles than the November 1960 activity sequence. Thus we rate July 1946 as the largest solar proton fluence event since 1942.

4

Routine solar flare observations started in 1932 with the development of the spectroheliosscope and the organization of the IAU solar flare patrol by Hale (1931). Prior to that time only an occasional solar flare was observed either in white light or by using a spectroheliograph. Therefore we must turn to these non-homogeneous solar records and proxy sources such as the geomagnetic parameters to determine if the nitrate peaks in 1928 and 1909 can be related to solar activity.

As mentioned previously the Ap index started in 1932. However, the geomagnetic aa index, which quantifies geomagnetic activity based on two antipodal stations has existed since 1868. As with the Ap* index, an AA* value can be derived from running means to determine the most disturbed 24-hour period.

Using the AA* list we find a major geomagnetic disturbance on July 7-8, 1928; this event ranks as the tenth largest for the 122-year record. Sunspot drawings on July 6 and 7 by H.H. Clayton of Canton, Massachusetts and the Greenwich records show a massive sunspot region just east of central meridian. We assume this was the region associated with the geomagnetic storm, and we further assume it was the source of a major solar proton event. For 1909 we likewise find a major geomagnetic storm on September 25-26; this storm ranks No. 8 on the AA* list with a value of 333. However, for this event there is a record of a solar flare on 24 September at 8 W (Newton, 1943). It is possible that this solar activity may have also produced a major proton event. Additional Antarctic snow core samples are necessary to verify the reality of the 1909 peak.

At the present time the events of the 22nd solar cycle are too recent to be verified by multiple detection in compacted snow sequences. However, preliminary measurements indicate a peak in 1989.

5. SUMMARY

We have found that the solar proton events with large peak fluxes as measured by ground-based cosmic ray detectors are primarily associated with solar activity at or near the western disk of the sun. Solar proton events with large fluences are primarily associated with solar activity near the solar central meridian which is subsequently related to a major geomagnetic storm a day or two later. The ice core measurements in the Antarctic have led us to select the proton event on 25 July 1946 as the probable largest solar proton fluence event since 1942. The use of historic solar observations and geomagnetic records coupled with the nitrate measurements in the ice core samples have aided in the identification of major events in 1909 and 1928. It is anticipated that even earlier events might be identified in this manner.

ACKNOWLEDGEMENTS

We wish to thank J.A. McKinnon of the National Geophysical Data Center for his help with the sunspot and flare identifications for 1928. The work at the University of Kansas was supported by USAF Contract AFOSR-88-0065.

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Appendix D

Possible Astrophysical Solution to the Solar Neutrino Problem

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ABSTRACT

Based on available solar neutrino and helioseismic data, a possible astrophysical solution to the solar neutrino puzzle is proposed. The apparent variation in solar neutrino flux shown by the chlorine experiment through nearly two solar cycles can be the result of time variations in the abundance and radial distribution of ^{7}Be in the solar core. Forthcoming high and low energy neutrino measurements and helioseismic experiments will allow verification of the mechanism proposed.

1. INTRODUCTION

During the past 20 years the radiochemical ^{37}Cl (ν_e, e^-) ^{37}Ar solar neutrino experiment (Davis and Cox, 1991) in the Homestake gold mine has been monitoring relatively high-energy neutrinos but throughout most of this time there were no other experiments that could either confirm or extend the results of the chlorine experiments. However, since the beginning of 1986, Kamiokande II (Hirata et al., 1991) has also been in operation with an electron energy detection threshold that makes it sensitive to the high energy part of the ^{8}B solar neutrino spectrum. It has been shown that neutrinos do come from the sun and that the energy spectrum is consistent with the known shape of the ^{8}B neutrino spectrum.

2. DISCUSSION OF RESULTS

In the Kamiokande experiment, the measured flux of ^{8}B neutrinos was (2.7 ± 0.5) $10^{6}/cm^{2}/sec$. Using this value we can estimate that the expected capture rate of the ^{37}Cl (ν_e, e^-) ^{37}Ar reaction should be $\approx$4 - 5 SNU (capture rates are expressed in terms of solar neutrino units, 10^{-36} captures per second per target atom). This value is in good agreement with the Homestake chlorine experiment data for the same time period, (4.2 ± 0.12) SNU (Davis and Cox, 1991). Moreover, a detailed analysis of the ^{37}Cl results for each individual extraction during the period January 1987 through April 1990 and for the Kamiokande II data (Hirata et al., 1991; Davis and Cox, 1991) show that there is general agreement between the two detector systems. This agreement between two completely different experiments is of primary importance.

Standard models (SSM) predict values of $(5.8 \pm 0.7)\ 10^6/cm^2/sec$ (Bahcall and Ulrich, 1988) and $(3.8 \pm 1.1)\ 10^6/cm^2/sec$ (Turk-Chieze et al., 1988) and these values are higher than the experimental results for ^8B neutrino flux. Note however that there is also an esssential difference between the two theoretical precdictions. In any case, it is clear that the measured flux of ^8B neutrinos is less than the theoretical prediction. Taking into account the very strong dependence of ^8B neutrino fluxes on the central temperature of the sun, $(T_c{}^{18})$, the high energy neutrino deficit can be explained if the actual central temperature is several percent lower than modern theory predicts.

An important result of the chlorine experiment is the apparent variation of the neutrino flux during two solar cycles. According to Davis and Cox (1991), the rate of the reaction $^{37}Cl\ (\nu_e, e^-)\ ^{37}Ar$ was lowest at solar maxima (0.4 ± 0.1) SNU (1979.5 – 1980.7) and (2.5 ± 0.5) SNU (1988.4 – 1990.3). During the last 2 solar minima the counting rate in the chlorine experiment was high (4.1 ± 0.9) SNU. The observed variation in the solar neutrino flux shown by the chlorine experiment has been considered by different authors in an attempt to search for an interconnection of solar surface and interior processes that might cause the phenomenon. The following conclusions have been formulated: (a) The ^{37}Ar production rate strongly anticorrelates with the monthly sunspot number and correlates directly with the solar diameter (Davis, 1987; Bahcall et al., 1982; Bieber et al., 1990; Davis and Cox, 1991). (b) There is an apparent correlation of the ^{37}Ar production rate with the magnetic field in the solar convection zone (Dorman and Wolfendale, 1991). (c) A tantalizing correlation between the variation in the low order acoustic solar oscillations over the solar cycle from 1977 to 1988 and the event rate in the ^{37}Cl detector over the same time period has been demonstrated (Krauss, 1990).

Based on the analysis of experimental data on solar neutrinos, helioseismology, solar irradience, sunspot number and semidiameter of the sun, the authors of this paper have suggested a possible astrophysical solution to the solar neutrino puzzle (Kocharov, et al., 1992; Kocharov, 1992). We concluded that during the solar cycle, the high energy neutrino flux changes because of variation in the ^7Be abundance in the solar core. ^8B neutrinos are generated by the reaction $^7Be\ (p, \gamma)\ ^8B$ in a very small central region (5% of the solar radius Ro) according to SSM (Bahcall and Ulrich, 1988; Turk-Chieze et al., 1988; Sackmann et al., 1990) the ^7Be abundance is highest at the center and decreases very rapidly with distance from the center. Thus, if the ^7Be abundance in a small central region is high during solar minimum and is low at solar maximum, the time variation of the ^{37}Ar production rate can be explained. A decrease of the ^7Be abundance in the region where ^8B nuclei are generated during the time interval from solar minimum to maximum can be caused by material moving from the extreme central portion to a region located at a distance of $r \approx 0.05$ Ro. During the time interval from solar maximum to minimum, the ^7Be abundance in the ^8B generation region is restored by the reaction $^3He\ (^4He, \gamma)\ ^7Be$ and the lifetime of the ^7Be ions in the solar interior is only several months (Kocharov, 1964). Thus

it is possible to have a low production rate of ^{37}Ar atoms at solar maximum and a high rate at solar minimum.

The problem of macroscopic motion in the solar core and its possible connection with variations of solar activity and neutrino fluxes has been considered very actively by D. O. Gough (see for example D. Gough, 1991, 1992, and references therin). It is shown that standard solar models are unstable and a possible consequence of this instability is substantial macroscopic fluid flow in the core, which not only modifies somewhat the mean stratification of temperature and density but also changes substantially the neutrino fluxes (D. Gough, 1993). Thus temporal variation of solar neutrino fluxes can be expected due to variation during the solar cycle of ^{7}Be abundance and radial distribution in the solar core. As we have already noted, (Kocharov et al., 1992) "there are real possibilities for temporal variation of the ^{37}Ar production rate. Very important now are new measurements of ^{8}B neutrino flux (chlorine and Kamiokande II experiments) and helioseismic data on the sun's internal rotation rate and on mixing processes in the ^{8}B generation region".

During the solar cycle we expect the capture rate in the gallium experiment to show a time variation due to the variation of ^{7}Be and ^{8}B neutrino fluxes. At solar minimum it is estimated to be close to SSM prediction (125 – 132) SNU and during solar maximum it will be (80–100) SNU.

3. CONCLUSIONS

There are now two gallium detector experiments in progress SAGE (Abazov et al., 1991) and GALLEX (Anselmann et al., 1992). The results in December 1992 were (58 ± 22) SNU (SAGE) and (83 ± 20) SNU (GALLEX). Both experiments collected data during the time period close to maximum solar activity (SAGE 1990–1991, GALLEX, 1992) and the relativly low rates of the ^{71}Ga (ν_e, e^-) ^{71}Ge reaction can be explained in the framework of our considerations. Thus, we would expect that, over the next several years, counting rates should increase in all of the four experiments reaching a maximum value during the next solar minimum.

We need not only new experimental data but also new solar models based on the advances in helioseismology. The experimental data on solar neutrinos, helioseismology, solar irradiance, sunspot number, solar wind and semidiameter of the sun obtained during the last several decades have considerably enhanced our knowledge of the sun. They show that there may be interconnections between processes occurring in different parts of the solar matter from the thermonuclear core to the solar atmosphere.

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Major Particle Events for Solar Cycles 5 to 22 in a Micro-Resolution Record of Nitrates from the Greenland Ice Sheet

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M A Shea and D F Smart (Space Physics Div., Geophysics Directorate/PL, Hanscom AFB, Bedford, MA 01731)

A 200-year micro-resolution time series of nitrate in snow has been obtained from the Central Greenland Ice Sheet. The nitrate concentrations have very high temporal resolution and have been evaluated for major solar particle events from 1800 to the present. The upper part of this record will be compared with equal resolution results from Antarctica. The nitrate yearly flux has been calculated through the period of solar cycles 5 to 22 for the evaluation of the solar signal contained in this sequence. A discussion will be presented of the hypothesis that the polar ice sheets contain signals of specific solar events (a) of major particle fluence which (b) are associated with major solar flares near the central meridian of the sun and (c) followed by large geomagnetic storms.

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A 200 Year Micro-Resolution Record of Nitrates and Conductivity for the Central Greenland Ice Sheet

E J Zeller and G A M Dreschhoff (Space Technology Center, 2291 Irving Hill Rd. Lawrence, KS 66045)

We measured nitrate and conductivity in the upper part of a firn core from the Central Greenland Ice Sheet at a resolution of 1.5 cm providing us with two time series of over 4000 data points each that extend through the year 1800 and shows both solar flare anomalies in nitrate as well as volcanic eruption events in conductivity, providing us with accurate dating of the record. Although our primary objective is to evaluate the solar signal to determine solar flare variability patterns, we recognize that the results may have important implications for short-term climatic variation. It has been reported that during some periods, climatic conditions over Central Greenland changed within only a few decades before settling into a new state. Our types of time series may help to define the nature of these variations and provide insight into their origins. We are currently working on a new analytical system to increase resolution and automate sampling.

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On the Solar Modulation of Cosmic Rays and Solar Flares During Deep Minima of Solar Activity

L D Martin (Natural History Museum, University of Kansas, Lawrence KS 66045)
G Kocharov (Physico-Technical Institute St. Petersburg, Russia)
G A M Dreschhoff and E J Zeller, (Space Technology Center Lawrence, KS 66045)

Records of solar flare and solar wind activity during periods of deep minima in solar activity (Maunder and Spoerer minima) can be investigated by means of measurements of cosmogenic isotopes in natural archives (tree rings and ice cores) and nitrate concentrations in polar ice. Available data on the time variation in deep interior processes within the sun can also be studied by measurements of neutrino fluxes and rotation rates. The possible interconnection of these processes with surface processes (sunspot number, irradience, diameter, helioseismology, and solar wind) furnish a basis for a discussion of the structure and mechanisms that operate within the body of the sun.

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4. SH

5. (a) SH04 History of the Solar Wind
   (b) 7519 Flares and mass ejectioms
   7544 Stellar interiors and dynamo theory
   7529 Photosphere and chromosphere

7. 20% in Radiocarbon

8. $ 50 Check Encl.

9. C

11. No

Temporal and Spatial Evaluation of the Solar Magnetic Field: a View from the Sidelines

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1. Satellite data on high energy solar flare particles and gamma rays contain information on temporal and spatial variation of the magnetic fields in the corona and upper chromosphere.
2. Experimental data on cosmogenic isotope abundance in dated natural archives (tree rings and ice cores) show that during deep minima of solar activity, cosmic rays were modulated significantly by variations in the solar magnetic field strength.
3. One of the possibilities of solving the solar neutrino puzzle requires very high magnetic field strength in the convective zone of the sun.
4. All available experimental data on high energy phenomena on the sun show that the total energy budget associated with flare phenomena requires that magnetic energy must be transported to the region of origin of the flare with high efficiency and that it must be applied effectively to acceleration of the charged particles. This paper seeks to examine the possibility that during the Maunder Minimum the modulation related to the solar cycle decreased and probably solar flare activity was increased.

1. 1993 Fall Meeting

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4. SH

5. (a) SH02 Genisis of Magneitc Activity on the Sun
(b) 7524 Magnetic fields, 7514 Energetic particles 7554 X rays and gamma rays

7. 20% Solar Physics, Radiocarbon

8. $50 Check Encl.

9. C

11. No